

SCREEN FOR SODIUM CHANNEL MODULATORS

Statement Regarding Federally Sponsored Research or Development

[0001] This invention was made under grant number 5RO1HL6607602 from the National Heart, Lung and Blood Institute. The government may have certain rights in the invention.

Field of the Invention

[0002] The invention relates to a method for screening compounds for use as anti-arrhythmic agents. The method employs a cell line that expresses a mutant sodium channel protein.

Background of the Invention

[0003] Mammalian voltage-gated sodium channels are pore-forming membrane proteins responsible for the initiation and propagation of action potentials in excitable membranes in nerve, skeletal muscle and heart cells. The controlled gating of sodium channels in response to membrane depolarizations is necessary for normal electrical signaling and establishing of intercellular communication. Voltage-gated Na⁺ ion channels consist of one large α -subunit (about 200 kDa) and one or two smaller β -subunits. The α -subunits are designated "Nav" (Na for sodium channel and v for voltage-gated), followed by a numbering system for the particular isoform. The Na⁺ channel α -subunit isoforms contain four homologous repeated domains (D1-D4) each with six transmembrane segments (S1-S6). The α -subunit protein alone forms a functional channel when expressed in mammalian expression systems. The four repeated domains are hypothesized to assemble as a pseudotetrameric structure with the permeation pathway situated at the center. Figure 1 is a cartoon depicting one conceptualization of how the Nav protein arranges itself with respect to the membrane. The cartoon is not accurate; it is an expanded model that does not attempt to depict how the four S6 segments come together to form the sodium channel, but it facilitates an understanding of how the

proteins might align with respect to the inside and outside of the excitable membrane. In fact, recent studies suggest that four S6 C-termini may jointly close the voltage-gated cation channel at the cytoplasmic side, probably as an inverted teepee structure.

[0004] Several pieces of evidence suggest that S6 segments are involved in Na⁺ channel gating. First, a number of receptors for various therapeutic drugs and neurotoxins such as local anesthetics (LAs), antiarrhythmics, anticonvulsants, antidepressants, pyrethroid insecticides, batrachotoxin (BTX), and veratridine, are situated at the middle of multiple S6 segments. Upon binding, these ligands exert their pharmacological actions on the Na⁺ channel, presumably in part via their corresponding S6 receptor. In particular, BTX drastically modifies Na⁺ channel activation, fast inactivation, and slow inactivation, suggesting that its receptor is linked to these gating processes.

[0005] The invention herein described arose from a hypothesis that S6 segments may be structurally geared for channel activation by lateral/rotational movement via a flexible gating hinge, a glycine or serine residue located at the middle of the inner Na⁺ channel S6 segments. This gating hinge could have two different conformations. One is in its relaxed straight α -helical form, which closes the channel at the S6 C-terminal end, and the other is the bendable α -helical form, which may bend outward at a 30° angle and thus splay open the channel at the S6 constricted C-terminus. After channel activation, S6 segments may then form the docking site for the fast-inactivation gate. A putative Na⁺ channel inactivation gate has been delineated at the intracellular linker between D3 and D4 by West et al. [Proc. Natl. Acad. Sci. USA 89:10910-10914 (1992)]. This linker could be situated at the C-termini of S6 segments, where the inactivation gate may plug the open channel while it binds to its docking site. This plugging mechanism has recently been demonstrated in voltage-gated K⁺ channels [Zhou et al., Nature 411:657-661 (2001)]. The foregoing hypothesis is useful because it provides a framework for interpreting the results and making predictions. However, it is

important to note that the invention is based on the results, not the hypothesis, and the hypothesis should not be viewed as a limitation on the claimed invention.

[0006] There is very close homology among the S6 segments of mammalian Nav proteins so far identified. This homology extends both through species and through isoforms of the Nav protein. As can be seen in the comparison below, the few variations that exist among the amino acids in the amino terminal portion of the S6 segments are very conservative replacements, and the carboxy terminal 11 amino acids of the S6 segments of all four domains are identical for rats and humans for both of the muscle sodium channel proteins Nav1.4 and Nav1.5:

D1S6

		1	6	11	16	21	26	
human	Nav1.1	YMIFF	<u>V</u> LVIF	LGSFY	L <u>I</u> NLI	LAVVA	MAY	(SEQ ID NO.: 1)
	Nav1.2	YMIFF	<u>V</u> LVIF	LGSFY	L <u>I</u> NLI	LAVVA	MAY	(SEQ ID NO.: 2)
	Nav1.3	YMIFF	<u>V</u> LVIF	LGSFY	L <u>I</u> NLI	LAVVA	MAY	(SEQ ID NO.: 3)
	Nav1.4	YMIFF	<u>V</u> <u>V</u> <u>I</u> IF	LGSFY	L <u>I</u> NLI	LAVVA	MAY	(SEQ ID NO.: 4)
	Nav1.5	YMIFF	MLVIF	LGSFY	LVNLI	LAVVA	MAY	(SEQ ID NO.: 5)
	Nav1.8	YMIFF	<u>V</u> <u>V</u> <u>V</u> IF	LGSFY	LVNLI	LAVVA	MAY	(SEQ ID NO.: 6)
rat	Nav1.4	YMIFF	<u>V</u> <u>V</u> <u>I</u> IF	LGSFY	L <u>I</u> NLI	LAVVA	MAY	(SEQ ID NO.: 8)
	Nav1.5	YMIFF	MLVIF	LGSFY	LVNLI	LAVVA	MAY	(SEQ ID NO.: 9)
	Nav1.6	YMIFF	MLVIF	VGSFY	PVNLI	LAVVA	MAY	(SEQ ID NO.: 10)
	Nav1.7	YMVFF	VVVIF	LGSFY	LVNLI	LAVVA	MAY	(SEQ ID NO.: 11)
	Nav1.8	YMVFF	MLVIF	LGSFY	LVNLI	LAVVA	MAY	(SEQ ID NO.: 12)

D2S6

		1	6	11	16	21	26	
human	Nav1.1	CLTVF	MMVMV	IGNLV	VLNLF	LALLL	SSF	(SEQ ID NO.: 13)
	Nav1.2	CLTVF	MMVMV	IGNLV	VLNLF	LALLL	SSF	(SEQ ID NO.: 14)
	Nav1.3	CLIVF	MLVMV	IGNLV	VLNLF	LALLL	SSF	(SEQ ID NO.: 15)
	Nav1.5	CLLVF	LLVMV	IGNLV	VLNLF	LALLL	SSF	(SEQ ID NO.: 16)
rat	Nav1.4	CLTVF	LMVMV	IGNLV	VLNLF	LALLL	SSF	(SEQ ID NO.: 17)

Nav1.5 CLLVF LLVMV IGNLV VLNLF LALLL SSF (SEQ ID NO.: 18)

D3S6

		1	6	11	16	21	26	
human	Nav1.1	MYLYF	VIFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 19)
	Nav1.2	MYLYF	VIFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 20)
	Nav1.3	MYLYF	VIFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 21)
	Nav1.4	MYLYF	VIFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 22)
	Nav1.5	MYIYF	VIFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 23)
	Nav1.8	MYLYF	VIFII	GGSFF	TLNLF	VGVII	DNF	(SEQ ID NO.: 24)
rat	Nav1.4	MYLYF	VIFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 25)
	Nav1.5	MYIYF	VVFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 26)
	Nav1.7	MYLYF	VVFII	FGSFF	TLNLF	IGVII	DNF	(SEQ ID NO.: 27)
	Nav1.8	MYIYF	VVFII	FGGFF	TLNLF	VGVII	DNF	(SEQ ID NO.: 28)

D4S6

		1	6	11	16	21	26	
human	Nav1.1	GI <u>F</u> FF	<u>V</u> SYII	ISFL <u>V</u>	VVNMY	IA <u>V</u> IL	ENF	(SEQ ID NO.: 29)
	Nav1.2	GI <u>F</u> FF	<u>V</u> SYII	ISFL <u>V</u>	VVNMY	IA <u>V</u> IL	ENF	(SEQ ID NO.: 30)
	Nav1.3	GI <u>F</u> FF	<u>V</u> SYII	ISFL <u>V</u>	VVNMY	IA <u>V</u> IL	ENF	(SEQ ID NO.: 31)
	Nav1.4	GI <u>C</u> FF	<u>C</u> SYII	ISFLI	VVNMY	IAIIL	ENF	(SEQ ID NO.: 32)
	Nav1.5	GILFF	TTYII	ISFLI	VVNMY	IAIIL	ENF	(SEQ ID NO.: 33)
rat	Nav1.4	GI <u>C</u> FF	<u>C</u> SYII	ISFLI	VVNMY	IAIIL	ENF	(SEQ ID NO.: 34)
	Nav1.5	GILFF	TTYII	ISFLI	VVNMY	IAIIL	ENF	(SEQ ID NO.: 35)

[0007] Except for a single I→V change at position 7 of D3S6, the rat and human Nav1.4 and Nav1.5 sequences are identical for all four S6 segments. Because of the very high degree of conservation (in fact identity) of the 11 amino acids at the carboxy termini of the S6 segments, the person of skill in the art expects that substitution in this region will have the same effect on sodium channel function across mammalian species and across isoforms of the Nav1 protein.

[0008] The numbering shown in the charts above is the standard numbering used to identify the 28 amino acids in the S6 segments by their position within that

segment. A separate system of numbering that may be applied to those same amino acids derives from their position within the sequence of the whole protein. Because the amino acid sequences of members of the Nav family of proteins vary widely outside the transmembrane regions, the protein sequence residue numbers assigned to the corresponding amino acids in the S6 segments differs among species and among sodium channel protein isoforms within species. Thus, the leucine identified as residue 19 in segment 6 in domain 1 (D1S6) is **L407** in human Nav1.5, **L408** in rat Nav1.5, **L441** in human Nav1.4 and **L435** in rat Nav1.4. Similarly, the isoleucine identified as residue 23 in segment 6 in domain 4 (D4S6) is **I1770** in human Nav1.5, **I1771** in rat Nav1.5, **I1581** in human Nav1.4 and **I1589** in rat Nav1.4. Unless otherwise noted, amino acids will be identified hereinafter, when referring to the whole protein, according to their position in rNav1.4. Thus **A438** refers to the alanine that occurs at position 438 in rNav1.4.

Summary of the Invention

[0009] In one aspect the invention relates to a method or screen for assessing the potential of a compound to treat a pathological condition, such as arrhythmia, which is manifested by an increased late sodium current in a heart. The method comprises:

- (a) providing a recombinant cell that expresses a mutant Nav 1 sodium channel protein;
- (b) measuring a first plateau current in the cell;
- (c) exposing the cell to a test compound;
- (d) measuring a second plateau current in the cell; and
- (e) comparing the first and second currents. A lower second current indicates that the test compound is a potential anti-arrhythmic agent. The mutant sodium channel protein has an amino acid sequence in which one or more amino acids among the ten amino acids occurring at the carboxy end of the S6 segments of D1, D2, D3 or D4 domains of mammalian Nav1 differs from the amino acid in wild-type Nav1 by substitution with tryptophan, phenylalanine, tyrosine or cysteine.

Mammalian Nav 1 proteins encompassed by the present invention encompass mammalian Nav1.1- Nav 1.9.

[0010] In another embodiment, the mutant sodium channel protein has an amino acid sequence in which one or more amino acids among the ten amino acids occurring at the carboxy end of the S6 segments of D1, D2, D3 or D4 domains of mammalian Nav1.4 or Nav 1.5 differs from the amino acid in wild-type Nav1 by substitution with tryptophan, phenylalanine, tyrosine or cysteine.

In another embodiment, the mutant sodium channel protein has an amino acid sequence in which at least one of amino acids 19, 21 and 22 of the S6 segment of D1 and amino acids 23 and 24 of the S6 segment of the D4 domain of mammalian Nav1 differs from the amino acid in wild-type Nav1 by substitution with tryptophan, phenylalanine, tyrosine or cysteine.

[0011] In another embodiment, the mutant sodium channel protein has an amino acid sequence in which at least one of amino acids 19, 21 and 22 of the S6 segment of D1 and amino acids 23 and 24 of the S6 segment of the D4 domain of mammalian Nav1.4 or Nav1.5 differs from the amino acid in wild-type Nav1.4 or Nav1.5 by substitution with tryptophan, phenylalanine, tyrosine or cysteine.

[0012] In another embodiment, the mutant sodium channel protein has an amino acid sequence in which at least one of amino acids L435, L437, A438, I1589 and I1590 of wild-type rNav1.4 is replaced by tryptophan, phenylalanine or tyrosine. L437 of rNav1.4 may be replaced by cysteine, in addition to tryptophan, phenylalanine or tyrosine.

[0013] In another aspect, the invention relates to an isolated nucleic acid comprising a nucleotide sequence that codes for a mutant mammalian Nav 1 protein. The mutant protein has a sequence as described above.

[0014] In another aspect, the invention relates to a cell transfected with a nucleic acid that encodes a mutant mammalian Nav1 protein. The mutant protein has a sequence as described above.

[0015] In another aspect, the invention relates to a functional recombinant sodium channel protein containing an amino acid sequence chosen from:

WILAVVAMAY	SEQ ID NO.: 36
YILAVVAMAY	SEQ ID NO.: 37
FILAVVAMAY	SEQ ID NO.: 38
LILWVVAMAY	SEQ ID NO.: 39
LILYVVAMAY	SEQ ID NO.: 40
LILFVVAMAY	SEQ ID NO.: 41
LICWVVAMAY	SEQ ID NO.: 42
LICYVVAMAY	SEQ ID NO.: 43
LICFVVAMAY	SEQ ID NO.: 44
WICWVVAMAY	SEQ ID NO.: 45
YICYVVAMAY	SEQ ID NO.: 46
FICFVVAMAY	SEQ ID NO.: 47
WICYVVAMAY	SEQ ID NO.: 48
WICFVVAMAY	SEQ ID NO.: 49
YICWVVAMAY	SEQ ID NO.: 50
FICWVVAMAY	SEQ ID NO.: 51
YICYVVAMAY	SEQ ID NO.: 52
FICFVVAMAY	SEQ ID NO.: 53
YICFVVAMAY	SEQ ID NO.: 54
FICYVVAMAY	SEQ ID NO.: 55
LIWAVWAMAY	SEQ ID NO.: 56
LIYAVWAMAY	SEQ ID NO.: 57
LIFAVWAMAY	SEQ ID NO.: 58
LILAVWAMAY	SEQ ID NO.: 59
MYIAWILENF	SEQ ID NO.: 60
MYIAYILENF	SEQ ID NO.: 61
MYIAFILENF	SEQ ID NO.: 62

MYIAIWLENF	SEQ ID NO.: 63
MYIAIYLENF	SEQ ID NO.: 64
MYIAIFLENF	SEQ ID NO.: 65
MYIACILENF	SEQ ID NO.: 66
MYIAICLENF	SEQ ID NO.: 67
MYIAWWLENF	SEQ ID NO.: 68
MYIAYYLENF	SEQ ID NO.: 69
MYIAFFLENF	SEQ ID NO.: 70

[0016] In another aspect, the invention relates to a functional recombinant sodium channel protein containing two sequences of amino acids. The first amino acid sequence is chosen from: WILAVVAMAY (SEQ ID NO.: 36); LILWVVAMAY (SEQ ID NO.: 39); LICWVVAMAY (SEQ ID NO.: 42); WICWVVAMAY (SEQ ID NO.: 45), and

LILAVWAMAY (SEQ ID NO.: 59). The second amino acid sequence chosen from: MYIAWILENF (SEQ ID NO.: 60); MYIAIWLENF (SEQ ID NO.: 63); MYIACILENF (SEQ ID NO.: 66); MYIAICLENF (SEQ ID NO.: 67), and MYIAWWLENF (SEQ ID NO.: 68).

Brief Description of the Drawings

[0017] **Figure 1** is a schematic representation of the rNav 1.4 Na⁺ channel protein in a cell membrane.

[0018] **Figure 2** illustrates the activation of wild-type and rNav 1.4-A438W co-expressed with $\beta 1$. Families of Na⁺ currents for wild type (A) and Nav 1.4-A438 mutant (B) were evoked by 5 ms pulses from the holding potential (-140 mV) to voltages ranging from -120 to +50 mV in 10-mV increments. The current traces evoked by a pulse to -50 mV and to +50 mV are labeled. Normalized membrane conductance (g_m) (C) was determined from the equation $g_m = I_{Na}/(E_m - E_{Na})$, where I_{Na} is the peak current, E_m is the amplitude of the pulse voltage, and E_{Na} is the reversal potential, and plotted against the pulse voltage. Plots were fitted with a

Boltzmann function, which yielded the midpoint voltage ($V_{0.5}$) and slope (k) for wild-type (open circles, $n = 5$) of -32.0 ± 0.9 mV and 8.7 ± 0.8 mV, respectively, and -38.8 ± 1.2 mV and 13.1 ± 1.1 mV for rNav1.5-A438W (closed circles, $n = 6$).

[0019] **Figure 3** is a schematic representation summarizing the effects of W- and selected C- mutations at C-termini of D1S6 and D4S6 on activation and inactivation gating.

[0020] **Figure 4** is a bar graph depicting the relative maintained currents in various W- and C-mutations at C-termini of D1S6 and D4S6. Fraction of non-inactivating current for D1S6 mutants (left), D4S6 (middle), and double and triple mutants (right). Cells were cotransfected with $\beta 1$ subunit; non-expressing mutants are noted with an X. The fraction of non-inactivating current was determined as the averaged current amplitude near 5 ms after the +50 mV pulse (e.g., Fig. 2) divided by the peak current. Error bars indicate standard error. Asterisks indicate significant differences from the wild-type channels as determined by a t test ($p < 0.05$, $n = 4-6$). Dotted line indicates the value of wild-type. Bars in gray indicate single C-substitution.

[0021] **Figure 5** shows the steady-state inactivation of wild-type and rNav1.4-A438W coexpressed with $\beta 1$. Superimposed Na^+ currents of wild type (A) and rNav1.4-A438W mutant (B) were evoked by a 5-ms test pulse to +30 mV. Test pulses were preceded by 100-ms conditioning pulses ranging from -160 mV and -15 mV in 5-mV increments. Notice that small non-inactivating inward currents appeared at conditioning voltages ≥ -60 mV. Cells were cotransfected with $\beta 1$ subunit. (C) Normalized Na^+ current availability (h_{∞}) of wild-type (open circle, $n = 5$) and rNav1.4-A438W (closed circle, $n = 5$) were plotted as a function of the 100-ms conditioning pulse voltage. Plots were fitted with the Boltzmann function. The fitted midpoint ($h_{0.5}$) and slope factor (k) for wild-type were -73.4 ± 0.1 mV and 5.0 ± 0.1 mV, respectively, and -89.0 ± 0.3 mV and 6.0 ± 0.2 mV for Nav1.4-A438W, respectively.

[0022] Figure 6 shows gating properties of rNav1.4-I1589W coexpressed with $\beta 1$. (A) Superimposed Na^+ current traces were evoked by 5-ms pulses from the holding potential (-140 mV) to voltages ranging from -120 to $+50$ mV in 10 -mV increments. (B) Superimposed currents were evoked by a 5-ms test pulse to $+30$ mV preceded by 100-ms conditioning pulses ranging from -160 mV to -15 mV in 5 -mV increments. (C) Normalized Na^+ conductance (g_m) was derived from (A) as described in the Fig. 2 legend, plotted against voltage, and fitted with a Boltzmann function. The fitted midpoint voltage ($V_{0.5}$) and slope (k) of the function for wild-type (open circles, $n = 5$) were -32.0 ± 0.9 and 8.7 ± 0.8 , respectively, and -19.0 ± 1.0 and 12.6 ± 0.9 , respectively for rNav1.4-I1589W (closed circles, $n = 6$). Normalized Na^+ current availability (h_∞) of wild-type (open down triangle, $n = 5$) and Nav1.4-I1589W (closed down triangle, $n = 5$) were derived from (B) as described in the Fig. 5 legend, and plotted as a function of conditioning voltage. Plots were fitted with the Boltzmann function. The midpoint ($h_{0.5}$) and slope factor (k) for wild-type were -73.4 ± 0.1 and 5.0 ± 0.1 , respectively, and -66.5 ± 0.2 and 5.7 ± 0.2 , respectively, for the Nav1.4-I1589W. Cells were cotransfected with $\beta 1$ subunit.

[0023] Figure 7 shows activation of rNav1.4-A438C and rNav1.4-I1589C coexpressed with $\beta 1$. Superimposed Na^+ current families of Nav1.4-A438C (A) and Nav1.4-I1589C (B) were evoked by 5-ms pulses from holding potential of -140 mV to voltages ranging from -120 to $+50$ mV in 10 -mV increments. (C) Normalized membrane conductance (g_m) plotted versus the amplitude of the 5-ms voltage step. G_m was determined as described in the Fig. 2 legend, plotted against the membrane voltage, and fitted with a Boltzmann function. The fitted midpoint voltage ($V_{0.5}$) and slope (k) of the function for wild-type (open circles, $n = 5$) were -32.0 ± 0.9 and 8.7 ± 0.8 , respectively, -25.9 ± 0.7 and 8.3 ± 0.6 for Nav1.4-A438C (closed square, $n = 5$), and -39.9 ± 1.1 and 10.9 ± 0.9 for Nav1.4-I1589C (closed triangle, $n = 6$). Cells were cotransfected with $\beta 1$ subunit.

[0024] Figure 8 shows activation gating of double and triple mutants.

Superimposed Na⁺ current families were evoked by 5-ms pulses from holding potential of -140 mV to voltages ranging from -120 to +50 mV in 10-mV increments for mutants A438W/I1589W (A), L437C/A438W (B), L435W/L437C/A438W (C), and I1589W/I1590W (D). All mutants were co-transfected with the β 1 subunit.

[0025] Figure 9. shows slow inactivation gating of double and triple mutants. To induce slow inactivation, we applied conditioning prepulses ranging from -180 mV to 0 mV with a duration of 10 s. After a 100-ms interval at -140 mV, Na⁺ currents were evoked by the delivery of a +30 mV test pulse. (A) Peak Na⁺ Currents were normalized to the corresponding current obtained with a prepulse to -180 mV and plotted against conditioning prepulse potential. Data were fitted with a Boltzmann function. The fitted $V_{0.5}$ values and k (slope factor) values from the Boltzmann functions were (in mV) -51.1 ± 0.5 and 9.7 ± 0.4 , respectively, for wild-type (open circle, $n = 5$); -49.9 ± 0.1 and 5.0 ± 0.1 , respectively, for L435W/L437C/A438W (closed circle, $n = 5$); -45.2 ± 0.3 and 5.8 ± 0.2 , respectively, for L437C/A438W (closed up triangle, $n = 5$); -45.2 ± 0.3 and 6.8 ± 0.3 , respectively, for A438W/I1589W (closed down triangle, $n = 6$); and -50.0 ± 0.9 and 9.5 ± 0.8 , respectively, for I1589W/I1590W (closed diamond, $n = 5$). The final steady-state non-inactivated values (in %) were 57.5 ± 0.4 (wild-type), 3.3 ± 0.4 (L435W/L437C/A438W), 12.3 ± 0.6 (L437C/A438W), 11.6 ± 0.8 (A438W/I1589W), and 3.4 ± 1.7 (I1589W/I1590W). All mutants are co-transfected with the β 1 subunit. (B) Development of slow inactivation. For the development of slow inactivation, the prepulse duration at +30 mV was varied ranging from 0 to 10s. The peak current at the test pulse of +30 was measured and normalized to the initial peak amplitude without a prepulse, and then plotted against the prepulse duration. The data were fitted by a single-exponential function. The τ values (and final steady-state Y_0 values) for wild-type, L435W/L437C/A438W, L437C/A438W, A438W/I1589W, and I1589W/I1590W

are 4.8 ± 0.3 s (51.6%), 0.72 ± 0.01 s (3.0%), 0.50 ± 0.01 s (16.6%), 0.64 ± 0.02 s (10.5%), and 0.81 ± 0.02 s (16.6%), respectively.

[0026] Figure 10 shows a coarse correlation between fast and slow inactivation gating. (A) The relative level of slow inactivation for D1S6 mutants (left), D4S6 (middle), and double and triple mutants (right). Non-expressing mutants are noted with an X. Values represent mean \pm S.E. of peak current elicited by a 5 ms test pulse to +30 mV preceded by a 10-s conditioning pulse to 0 mV and a 100ms interval at -140 mV as described in Fig. 9A. Asterisks indicate significant differences from the wild-type channels as determined by a t test ($p < 0.05$). Dotted line indicates the value of wild-type. Bars in gray indicate single C-substitution. (B) The fraction of slow-inactivated current vs. the fraction of non-inactivating current of the individual mutant. Data for wild type and mutants were taken from Fig. 4 for x axis and from Fig. 10A for y axis. The mutants are labeled. The solid line is the linear fit of the complete data set with a correlation coefficient (r) of 0.61. Mutants with impaired fast inactivation (fraction of non-inactivating current $> 5\%$) are shown at the right-hand side of the dashed line; all of them show enhanced slow inactivation.

[0027] Figure 11 depicts voltage dependence of flecainide block in rNav1.4 channels. Conditioning prepulses ranging from -180 mV to -10 mV were applied for 10s. After a 100-ms interval at -140 mV, Na^+ currents were evoked by a test pulse at +30 mV for 5-ms. Currents recorded before (open circle, $n = 6$) and after 30 μM flecainide (closed circle, $n = 6$) were normalized to the current obtained at the -180 mV conditioning pulse and plotted against the conditioning voltages. Flecainide data were then renormalized at each voltage with respect to the control value without flecainide. Data were fitted with a Boltzmann function ($1/[1+\exp((V_{0.5}-V)/k_E)]$). The average $V_{0.5}$ value and k_E (slope factor) value for the fitted functions were (in mV) -47.9 ± 1.1 and 8.6 ± 0.9 , respectively, for control and -57.3 ± 2.7 and 17.6 ± 2.1 , respectively, for flecainide.

[0028] Figure 12 shows blockade of inactivation-deficient Nav1.4 L435W/L437C/A438W channels at various flecainide concentrations. Superimposed Na^+ currents evoked by a 140 ms test pulse to +30 mV every 30 seconds were shown at various flecainide concentrations. Steady state block at each concentration was achieved within 5 min.

[0029] Figure 13 shows the decay phase of the Na^+ current; the decay phase of the Na^+ current was fitted with a single exponential function, and the corresponding time constant (τ) was inverted and plotted against the corresponding concentration. Data were fitted with a linear regression $y = 14.9x + 12.16$ (solid line). On-rate (k_{on}) corresponded to the slope of the fitted line ($14.9 \mu\text{M}^{-1}\text{s}^{-1}$) and the off-rate (k_{off}) corresponded to the y-intercept (12.16 s^{-1}). The dissociation constant was determined by the equation $K_D = k_{\text{off}}/k_{\text{on}}$ and equaled $0.81 \mu\text{M}$.

Detailed Description of the Invention

[0030] The first aspect of the invention relates to a screen for assessing the potential of a compound to treat a pathological condition, such as arrhythmia, which is manifested by an increased late sodium current in a heart. The method comprises:

- (a) providing a cell that expresses a recombinant mutant Nav1 sodium channel protein;
- (b) measuring a first plateau current in the cell;
- (c) exposing the cell to a test compound;
- (d) measuring a second plateau current in the cell; and
- (e) comparing the first and second currents. A lower second current indicates that the test compound is a potential anti-arrhythmic agent. The mutant sodium channel protein has an amino acid sequence in which one or more amino acids among the ten amino acids occurring at the carboxy end of the S6 segments of D1, D2, D3 or D4 domains of a mammalian Nav1 differs from the amino acid in wild-type Nav1.4 or by substitution with tryptophan, phenylalanine, tyrosine or

cysteine. In a preferred embodiment, the mutant sodium channel protein has an amino acid sequence in which at least one amino acid chosen from amino acids 19, 21 and 22 of the S6 segment of D1 and amino acids 23 and 24 of the S6 segment of the D4 domain of a mammalian Nav1 is the amino acid that is replaced. These amino acids correspond to amino acids L435, L437, A438, I1589 and I1590 of wild-type rNav1.4. The wild-type amino acids may be replaced by tryptophan, phenylalanine or tryrosine, all of which are neutral, hydrophobic and bulky - the important common features for impairing the so-called “fast inactivation” of the sodium channel. Certain of the wild-type amino acids may also be replaced by cysteine. Cysteine produces a similar impairment of fast inactivation, but appears to do so by an indirect route, whereby it achieves effective bulkiness (and hydrophobicity) through reaction of the sulfhydryl with physiologically accessible nucleophiles. The experiments described below were carried out with tryptophan and cysteine.

[0031] The remainder of the Nav protein – outside the S6 segments – is optimally the sequence of a Nav 1 sodium channel protein, for example, Nav 1.1, Nav 1.2, Nav 1.3, Nav 1.4, Nav 1.5, Nav 1.6, Nav 1.7, Nav 1.8 or Nav 1.9. Nav1.4 and Nav1.5 are the two isoforms of the Nav protein that are found in skeletal and heart muscle; the remaining isoforms have been primarily identified in the CNS and neuronal structures. In one embodiment, a leucine corresponding to L437 of rNav1.4 is replaced with cysteine, and one or both of a leucine and an alanine corresponding to L435 and A438 respectively are replaced with tryptophan. In other embodiments, alanine corresponding to A438 and an isoleucine corresponding to I1589 are replaced, preferably by tryptophan. Preferred sequences of the residues 19-28 of the S6 segment are:

WILAVVAMAY	SEQ ID NO.: 36
YILAVVAMAY	SEQ ID NO.: 37
FILAVVAMAY	SEQ ID NO.: 38
LILWVVAMAY	SEQ ID NO.: 39
LILYVVAMAY	SEQ ID NO.: 40
LILFVVAMAY	SEQ ID NO.: 41

LICWVVAMAY	SEQ ID NO.: 42
LICYVVAMAY	SEQ ID NO.: 43
LICFVVAMAY	SEQ ID NO.: 44
WICWVVAMAY	SEQ ID NO.: 45
YICYVVAMAY	SEQ ID NO.: 46
FICFVVAMAY	SEQ ID NO.: 47
WICYVVAMAY	SEQ ID NO.: 48
WICFVVAMAY	SEQ ID NO.: 49
YICWVVAMAY	SEQ ID NO.: 50
FICWVVAMAY	SEQ ID NO.: 51
YICYVVAMAY	SEQ ID NO.: 52
FICFVVAMAY	SEQ ID NO.: 53
YICFVVAMAY	SEQ ID NO.: 54
FICYVVAMAY	SEQ ID NO.: 55
LIWAVWAMAY	SEQ ID NO.: 56
LIYAVWAMAY	SEQ ID NO.: 57
LIFAVWAMAY	SEQ ID NO.: 58
LILAVWAMAY	SEQ ID NO.: 59
MYIAWILENF	SEQ ID NO.: 60
MYIAYILENF	SEQ ID NO.: 61
MYIAFILENF	SEQ ID NO.: 62
MYIAIWLENF	SEQ ID NO.: 63
MYIAIYLENF	SEQ ID NO.: 64
MYIAIFLENF	SEQ ID NO.: 65
MYIACILENF	SEQ ID NO.: 66
MYIAICLENF	SEQ ID NO.: 67
MYIAWWLENF	SEQ ID NO.: 68
MYIAYYLENF	SEQ ID NO.: 69
MYIAFFLENF	SEQ ID NO.: 70

[0032] The resultant protein may also contain a second amino acid sequence, YMIFFX^aX^bX^cIFLGSFYLYX^dN (SEQ ID NO. 71), amino-terminal to the foregoing amino acid sequence. In the second sequence, X^a is V or M; X^b is L or V; and X^c and X^d are independently I or V. These variable residues account for the variants thus far observed in S6 residues 1-18 of mammalian Nav proteins. For example, one S6 sequence according to the invention would be YMIFFMLVIFLGSFYLVNWILAVVAMAY (SEQ ID NO. 72).

[0033] As will be evident, functional recombinant sodium channel proteins may contain multiple sequences of amino acids altered in the S6 segments of different domains. In preferred multiple-sequence embodiments, a first amino acid

sequence may be chosen from: WILAVVAMAY (SEQ ID NO. 36); LILWVVAMAY (SEQ ID NO. 37); LICWVVAMAY (SEQ ID NO. 42); WICWVVAMAY (SEQ ID NO. 45), and LILAVWAMAY (SEQ ID NO. 59), and a second amino acid sequence chosen from: MYIAWILENF (SEQ ID NO. 60); MYIAIWLENF (SEQ ID NO. 63); MYIACILENF (SEQ ID NO. 66); MYIAICLENF (SEQ ID NO. 67), and MYIAWWLENF (SEQ ID NO. 68). For obvious reasons, the two S6 sequences will not commonly be adjacent each other in primary sequence. In fact, in preferred embodiments, the sequences will be separated by at least 400 amino acid residues, and, when the sequences reflect S6 segments in domains 1 and 4, they will be separated by at least 1000 residues.

[0034] In another aspect, the invention relates to a cell comprising a recombinant nucleic acid that encodes a mutant mammalian Nav1 protein. The mutant protein has a sequence as described above, and the cell expresses sodium channels that exhibit a plateau current of greater than 1 nanoamp. The process for transfecting a cell with an appropriate nucleic acid is well known in the art. The particular cell chosen for transfection was the human embryonic kidney (HEK293t) cell. Chinese hamster ovary cells are also well suited for this purpose. The person of skill will be aware of cell lines that become known in the art for their ability to express proteins of the size (200 kDa) of the Nav protein, and these will be appropriate for transfection with the nucleic acids of the invention. Any eukaryotic cells which support stable replication of plasmids containing nucleic acids encoding the mutant sodium channels described above may be used in practicing the invention. Non-limiting examples of host cells for use in the present invention include HEK 293 cells (American Type Culture Collection, Manassas, VA (ATCC Cat. No. CRL-1573), CV-1/EBNA-1 cells (ATCC Cat. No. CRL 10478), HeLa cells, D98/raji cells, 293EBNA (Invitrogen, Cat. No. R62007), CV-I cells (ATCC Cat. No. CCL 70) and 143B cells (ATCC Cat. No. CRL-8303). In addition, primary cultures of eukaryotic cells may be isolated from their tissue of origin and transfected with the appropriate expression vector.

[0035] One of the advantages of the substitutions of the present invention is that, unlike all previously reported mutants of the Nav protein, substitution with W, F, Y or C in the carboxy terminal ten residues of S6, when expressed at a useful level, results in a cell line that is viable (the leakage is not lethal to the cell), while at the same time the cells exhibit a large enough sodium channel current to make measurement reliable.

[0036] In practicing the present invention, many conventional techniques in molecular biology, microbiology, and recombinant DNA are used. Such techniques are well known and are explained in, for example, Sambrook et al., 2001, Molecular Cloning: A Laboratory Manual, Third Edition, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York; DNA Cloning: A Practical Approach, Volumes I and II, 1985 (D. N. Glover ed.); Oligonucleotide Synthesis, 1984 (M.L. Gait ed.); Nucleic Acid Hybridization, 1985, (Hames and Higgins, eds.); Transcription and Translation, 1984 (Hames and Higgins, eds.); Animal Cell Culture, 1986 (R.I. Freshney ed.); Immobilized Cells and Enzymes, 1986, (IRL Press); Perbas, 1984, A Practical Guide to Molecular Cloning; the series, Methods in Enzymology (Academic Press, Inc.); Gene Transfer Vectors for Mammalian Cells, 1987 (J.H. Miller and M.P. Calos eds., Cold Spring Harbor Laboratory); and Methods in Enzymology Vol. 154 and Vol. 155 (Wu and Grossman, and Wu, eds., respectively); Current Protocols in Molecular Biology, John Wiley & Sons, Inc. (1994), and all more current editions of these publications. Throughout this application, various references are referred to within parentheses or square brackets. The disclosures of these publications in their entireties are hereby incorporated by reference as if written herein.

[0037] In the description that follows, certain conventions will be followed as regards the usage of terminology. The term "expression" refers to the transcription and translation of a structural gene (coding sequence) so that a sodium channel protein (i.e. expression product) having biological activity is synthesized. It is understood that post-translational modifications may remove portions of the polypeptide that are not essential and that glycosylation and other

post-translational modifications may also occur. The term "transfection," as used herein, refers to the uptake, incorporation and expression of exogenous DNA into a host cell by any means, and includes, without limitation, transfection of plasmids, episomes and other circular DNA forms. The expression vector may be introduced into host cells via any one of a number of techniques including but not limited to viral infection, transformation, transfection, lipofection or other cationic lipid based transfection, calcium phosphate co-precipitation, gene gun transfection, and electroporation. These techniques are well known to persons of skill in the art.

[0038] The term "sodium channel protein" refers to any protein that provides a functional sodium channel in an excitable membrane. Known sodium channel proteins are the isoforms of the Nav family: Nav1.1 through Nav 1.9, Nav 2.1 through Nav2.3 and Nav 3.1. [See Goldin Ann.N.Y.Acad.Sci 868:38-50 (1999)]. For the present invention, type I Nav proteins (referred hereinafter as Nav 1 or Nav 1.x) are preferred, with Nav1.4 and Nav1.5 being more preferred. The term "mutant sodium channel protein" or "recombinant sodium channel protein" refers to a recombinant protein having the sequence of a Nav 1 protein, that is, Nav1.1 through Nav 1.9, in which from one to ten amino acids differ from the wild-type. The person of skill will of course recognize that in proteins of 2000 amino acids, such as those of the Nav family, there can be innumerable deletions, insertions and substitutions that do not affect the function of the protein in any measurable way. Proteins having >90% homology to a protein in the Nav family but containing deletions, insertions and substitutions that do not affect their function in providing a sodium channel are to be considered equivalents of the claimed mutants. Furthermore, because the genetic code is degenerate, more than one codon may be used to encode a particular amino acid, and therefore, the amino acid sequence can be encoded by any set of similar DNA oligonucleotides. With respect to nucleotides, therefore, the invention encompasses all the DNA sequences containing alternative codons, which code for the eventual translation of the identical amino acid.

[0039] The term “plateau current” refers to the current measured in a single cell 5 ms after activation by a sufficient voltage pulse to open the channel. For cells expressing wild-type Nav1.4 and 1.5 the pulse is -60 ± 10 mV and the plateau current is below 1 nA. For cells expressing mutant Nav1.4 and 1.5 according to the invention, the pulse can be somewhat higher (e.g. -70 ± 10 mV) and the plateau current is above 1 nA.

The utility of the mutant Nav test system has been demonstrated with flecainide. Flecainide is one of several orally active class Ic antiarrhythmic drugs. The primary target of flecainide is the cardiac Na^+ channel, which is responsible for the upstroke of cardiac action potentials. Recently, flecainide has been found effective for patients with the Long QT syndrome [Windle, et al., Ann. Noninvasive Electrocardiol. 6(2):153-158 (2001)]. The state-dependent binding of flecainide with wild type and an exemplary inactivation-deficient sodium channel of the invention (rNav1.4-L435W/L437C/A438W) were compared in the HEK293t expression system. Unlike the inactivation-deficient cardiac Nav1.5 IFM/QQQ mutant of Grant et al. [*Biophysical J.* 79:3019-3035 (2000)], the channel of the invention expressed well, which is evident from the large sodium currents (>1 nanoamp following -50mV stimulation), and we demonstrate below that flecainide binds rapidly and preferentially with the open state but minimally with the resting state. This provides the basis for the first truly useful, high-throughput screen for agents that may be used to treat various pathological conditions that manifest an increase in persistent late sodium currents in the heart. Such agents include antiarrhythmic agents. To screen for such agents, one follows the procedure described in the experiments described below, and one simply replaces flecainide by a test agent.

[0040] The invention began from the hypothesis that an amino acid having a bulky hydrophobic side chain, would disrupt or alter channel function because of its large size. The disruption or alteration would occur if a large hydrophobic amino acid were substituted for an amino acid that contacts or directly interacts with other parts of the channel protein. In addition, it was possible that the effects

of several residues on the fast inactivation gating would be additive after multiple substitutions. The experiments below employed tryptophan (W) and cysteine (C) as the prototypic bulky, hydrophobic amino acids.

[0041] In practicing the method of the invention, a mammalian mutant Nav 1 sodium channel protein is expressed in an appropriate cell. The cell expressing the sodium channel of the invention is contacted with a compound to determine whether the compound has potential utility as an anti-arrhythmic agent. Isolated nucleic acids comprising a nucleotide sequence that codes for a mutant mammalian Nav 1 protein according to the invention may be obtained by methods known to one of skill in the art. Site-directed mutagenesis of DNA from appropriate cells, for example, heart and smooth muscle, or cell line cultures of the appropriate species or tissue, is then performed to obtain a nucleic acid encoding mutant sodium channel protein as described above.

Isolation of DNA

[0042] DNA encoding a Na⁺ channel, in accordance with the instant invention, may be obtained by screening reverse transcripts of mRNA or cDNA from appropriate cells or tissues, for example, CNS, skeletal muscle, denervated skeletal muscle, cardiac muscle, uterus, astrocytes or cell line cultures of the appropriate tissues, by screening genomic libraries, or by combinations of these procedures. Screening of mRNA, cDNA or genomic DNA may be carried out with oligonucleotide probes generated from the nucleic acid sequence information of the sodium channel proteins disclosed herein.

[0043] An alternative means to isolate the gene encoding a Nav sodium channel protein is to use polymerase chain reaction (PCR) methodology as described in Sambrook et al., *Molecular Cloning: A Laboratory Manual*, second edition, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York.

Site-directed mutagenesis

[0044] The QUIKCHANGE XL™ site-directed mutagenesis kit (Stratagene, La Jolla, CA) was used to create rat skeletal muscle Nav1.4 mutant clones as previously described (Wang and Wang, *Biophys. J.* 72:1633-1640, 1997; Wang and Malcolm, *BioTechniques* 26:680-682, 1999). Preliminarily, a wild type rNav1.4-pcDNA1/Amp clone was generated to serve as the template for mutagenesis. Briefly, a cDNA insert prepared from the wild type rat muscle cDNA Nav 1.4, clone μ l-2, (Genbank accession number M26643) (Trimmer et al., *Neuron* 3: 33-49, 1989) was cloned into the EcoRI site of a pcDNA1/Amp vector (Invitrogen, Carlsbad, CA) to yield the vector rNav 1.4-pcDNA1/Amp. For mutagenesis, two complementary mutant oligonucleotides of 38-42 nucleotides in length (see Table 1) are annealed to the template DNA in separate tubes for 4 cycles of PCR reaction (94° C, 30 sec; 55° C, 1 min, 68° C, 23 min).

Table 1**Primers for Site-Directed Mutagenesis**

Clones rNav 1.4 437C438W/ rNav 1.4 435W437C438W:

5'- ctcacatcaatctgatctgctgggtgggtggccatggcgtag - 3' (SEQ ID NO.: 73)

5'- cctcatcaattggatctgctgggtgggtggccatggcgtag- 3' (SEQ ID NO.: 74)

Clones hNav 1.4 443C444W/ hNav 1.4 441W443C444W

5'- cctcatcaatctgatctgctgggtgggtggccatggcatatg - 3' (SEQ ID NO.: 75)

5'- gctctttctacatcatcaattggatctgctgggtgggtggccatggcatatgc - 3' (SEQ ID NO.: 76)

hNav 1.5 409C410W

5'- cctggtgaacctgatctgctgggtgggtcgcaatggcc - 3' (SEQ ID NO.: 77)

5'- ccttctacctggtgaactggatctgctggg - 3' (SEQ ID NO.: 78)

[0045] The PCR reaction mix contains template DNA (0.4 ng/ul), primer (5ng/ul), KCl (10mM), (NH₄)₂SO₄ (10mM), Tris-HCl (pH8.8) (20mM), MgSO₄ (2mM), TritonX-100 (0.1%), 0.1 mg/ml bovine serum albumin, deoxynucleotides mix (0.4mM each), pfuTurbo DNA polymerase (0.05 U/ul). The stage 2 PCR reactions follow after mixing the two primer stage 1 reactions into one and perform the following PCR reactions: 94 °C, 30 sec, 18 cycles of (94 °C, 30sec, 55 °C , 1 min; 68 °C, 23 min). The in vitro synthesized DNA is digested with DpnI at 0.2 U/ul at 37 °C for one hour. One µl of the DpnI treated DNA is transformed into XL-Gold ultracompetent cells (Stratagene, La Jolla CA), plated on Ampicillin (50 ug/ml) LB plates. Bacterial colonies are picked into LB containing Ampicillin at 50 ug/ml DNA. The mutation frequency is 25-100 %, that is, you will obtain at least one mutant if you sequence 4 clones.

[0046] To minimize the possibility that unique phenotypes are due to unwanted mutations, independent clones of rNav1.4-L435W/L437C/A438W and rNav1.4-L437C/A438W as well as additional homologous L435W/L437C/A438W clones from human isoforms (hNav1.4 and hNav1.5) were created. Preliminary results showed that all of these independent and homologous clones displayed comparable phenotypes to those of rNav1.4 counterparts. DNA sequencing near the mutated site was performed to confirm the mutations.

Transient transfection

[0047] Transfection methods are well known in the art. In one embodiment, human embryonic kidney (HEK293t) cells were grown to ~50% confluence in DMEM (Gibco) containing 10% fetal bovine serum (HyClone, Logan UT), 1% penicillin and streptomycin solution (Sigma, St. Louis, MO), 3 mM taurine, and 25 mM HEPES (Gibco). HEK293t cells were then transfected with cloned Na⁺ channels, either wild type or mutant, by a calcium phosphate precipitation method in a T1-25 flask (Cannon and Strittmatter, 1993). A reporter plasmid CD8-pih3m and cDNA clone in the pcDNA1/amp vector (Invitrogen, San Diego, CA) were prepared in 250 mM CaCl₂, added to a test tube containing 0.36 ml of Hanks' balanced salt solution and incubated at 22°C for 20 min. The DNA solution was then dripped over a cell culture (30–50% confluence) containing 7 ml of DMEM. The transfected cells were trypsinized and replated 15 h later to an appropriate density in 35-mm tissue culture dishes containing 2 ml of fresh DMEM. Transfected cells were maintained at 37°C in a humidified 5% CO₂ incubator, and used after 1-4 days. Transfection-positive cells, which were identified by binding to immunobeads (CD8-Dynabeads, Dynal, Lake Success NY) coated with a monoclonal antibody specific for CD8 antigen, were selected for patch-clamp experiments.

[0048] Transfection of wild type rNav1.4-pcDNA1/Amp or mutant clones (5-10 µg) along with β1-pcDNA1/Amp (10-20 µg) and reporter CD8-pih3m (1 µg) generated sufficient sodium channel expression for later current recording.

Stable Transfection

[0049] For stable transfection, a selectable marker plasmid is included in the expression vector. Generally, a drug resistance gene, for example, *pac*, which confers resistance to the antibiotic puromycin is used. After transfection, the cells are trypsinized, transferred into large culture dishes and treated with the antibiotic for which resistance has been conferred by the plasmid. A drug killing curve should be determined for each batch of drug solution and cells. Two to three weeks after transfection, drug resistant colonies are picked, amplified, and analyzed for channel expression. Other types of selectable markers include, for example, geneticin (Invitrogen, Carlsban, CA), and hygromycin and can be used to obtain permanent cell lines for sodium channel expression.

Measurement of Na⁺ Current

[0050] Whole-cell configuration was used to record Na⁺ currents according to the method of Hamill et al. [Pflugers Arch. 391:85-100 (1981)]. Borosilicate micropipettes (Drummond Scientific Company, Broomall, PA) were pulled with a puller (P-87, Sutter Instrument Company, Novato, CA) and heat polished. Pipette electrodes contained 100 mM NaF, 30 mM NaCl, 10 mM EGTA, and 10 mM HEPES adjusted to pH 7.2 with CsOH. The pipette electrodes had a tip resistance of 0.5 to 1.0 MΩ. Access resistance was 1-2 MΩ and was further reduced by series resistance compensation. All experiments were performed at room temperature (22-24°C) under a Na⁺-containing bath solution with 65 mM NaCl, 85 mM choline Cl, 2 mM CaCl₂, and 10 mM HEPES adjusted to pH 7.4 with tetramethylammonium hydroxide. Residual outward currents were evident in some cells at voltages ≥ +30 mV; these currents were present in untransfected cells and were insensitive to tetrodotoxin. These residual currents were not subtracted from the measurements. Whole-cell currents were measured by an AXOPATCH 200B™ (Axon Instruments, Foster City, CA) or an EPC-7 (List Electronics, Darmstadt/Eberstadt, Germany), filtered at 3 kHz, collected, and analyzed with pClamp8 software (Axon Instruments). Leak and capacitance were subtracted by the patch clamp device and further by the leak subtraction protocol

(P/-4). Cells were held at -140 mV for functional characterizations. Voltage error was <4 mV after series resistance compensation. An unpaired Student's *t* test was used to evaluate estimated parameters (mean \pm SEM or fitted value \pm SE of the fit); *P* values of < 0.05 were considered statistically significant.

[0051] Gating properties of W substitutions within the C-terminus of D1S6 in Nav1.4 Na⁺ channels were examined. To characterize the effects of W substitutions, we measured Na⁺ currents of D1S6 W-substituted mutant channels at various voltages. Each of residues 19 to 28 (the carboxy terminus of S6) was replaced by W. As an example, Fig. 2 A and B show the superimposed current families of Nav1.4 wild type and mutant Nav1.4-A438W (position 22 at D1S6) cotransfected with $\beta 1$ subunit, respectively. Activation threshold was around -50 mV for wild type and around -60 mV for A438W mutant channels. The peak conductance was calculated as described in the figure legend, normalized, and plotted against the corresponding voltage (Fig. 2C). Voltage dependence of activation was fitted by a standard Boltzmann equation and the W mutant showed an apparent leftward shift of -6.8 ± 2.1 mV ($n = 6$). **Figure 3** is a summary of effects of W- and selected C-mutations at C-termini of D1S6 and D4S6 on activation and inactivation gating. In the left panel is a vertical representation of amino acid sequences of D1S6 (top), D4S6 (middle), and double and triple mutants (bottom). All mutants and wild-type Na⁺ channels were co-transfected with the $\beta 1$ subunit. **Activation Shift:** the bar graph shows the differences in voltage for the half-maximal activation ($V_{0.5}$) of the wild-type and mutant Na⁺ channels. The $V_{0.5}$ values (mean \pm SEM) were obtained from the Boltzmann fits of normalized conductance versus voltage plots as described above for **Figure 2**. Significantly, the estimated reversal potential (E_{Na}) remained about the same in these mutants. Bars in gray indicate single C-substitution. Non-expressing mutants are noted with an X. **Slope Effect (Activation, Inactivation):** this bar graph shows the differences in *k* values for the wild-type and mutant channels. The *k* values (mean \pm SEM) were obtained from Boltzmann fits of *I/V* plots (activation) and from Boltzmann fits of steady-state inactivation plots

(inactivation), as described for **Figure 2** and **Figure 5**, respectively. **Inactivation Shift:** the bar graph shows the differences in voltage for the half-maximal inactivation ($h_{0.5}$) of the wild-type and mutant Na^+ channels. The $h_{0.5}$ values (mean \pm SEM) were obtained as described for **Figure 5**. All values were derived from $n = 4-6$, except E1592W with $n = 3$. An asterisk (*) indicates that the value is statistically different from that of the wild type ($p < 0.05$). Except for L435W and I436W, all other D1S6 mutants W displayed a leftward shift. L437W shifted leftward by as much as -22.1 ± 2.0 mV ($n = 5$). The slope factor for each W mutant showed either no significant change or became less steep.

[0052] Another noticeable change in gating after A438W substitution was the non-inactivating currents maintained at the end of the pulse (Fig. 2B vs. 2A). To quantify this difference between wild type and mutant channels we measured the amount of the non-inactivating maintained current near the end of 5-ms +50 mV pulse. The wild-type current decayed rapidly and reached its steady-state level within 2-3 ms and 2.9 ± 0.8 % ($n = 5$) of currents were maintained under these experimental conditions. In contrast, Nav1.4-A438W mutant showed conspicuous maintained currents under identical conditions. As measured near the 5-ms time, 31.9 ± 4.2 % ($n = 6$) of currents were non-inactivating. Thus, a substitution of W at position 22 of D1S6 impairs the Na^+ channel fast inactivation significantly ($P < 0.001$). The relative non-inactivating components of all mutants at D1S6 are listed in Figure 4 (left section). The two other W mutants with impaired fast inactivation are L435W (Fig.4; the fraction of non-inactivating current = 0.10 ± 0.02 , $n = 5$, $P < 0.05$; position 18) and L437W (0.055 ± 0.017 , $n = 5$, $P = 0.20$; position 21).

[0053] Using various conditioning pulses from -160 mV to -15 mV, we further characterized the steady-state inactivation of the mutant channels. Figure 5A and B show Na^+ currents of the wild type and Nav1.4-A439W mutant, respectively, under these pulse conditions. Peak currents were measured, normalized with respect to the peak current at -160 mV and plotted against conditioning voltages

(Figure 5C). Clearly, a non-inactivating component was again present in Nav1.4-A438W mutant channels. The data were fitted with a standard Boltzmann equation and the shift in the $\Delta V_{0.5}$ is shown in Figure 3 (top on right side) along with the shift in the slope factor, the Δk value.

[0054] The residues from position 19 to 26 in D4S6 were also substituted with tryptophan (Figure. 1; solid bracket). Figure 6 A and B show the current voltage relationship and steady state inactivation measurement of mutant Nav1.4-I1589W, respectively. Figure 6C shows the normalized peak conductance and h_{∞} measurements against voltage of this mutant channel. Again there were significant non-inactivating currents maintained at the end of test pulse for I1589W. The relative amounts of the maintained currents of all mutants at D4S6 are listed in Figure 4 (middle section) along with D1S6 mutants. The activation of I1589W was shifted rightward by 13.0 ± 1.9 mV ($n = 6$) and the steady state inactivation was shifted rightward by 6.8 ± 0.3 mV ($n = 5$). These changes in gating parameters of all D4S6 mutants are listed in Figure 3 (middle section). Two W mutant channels (I1589W and I1590W) appeared to have significantly impaired fast inactivation. Two mutants, I1587W and A1588W, expressed Na^+ currents below 1 nA in this expression system.

[0055] There is not a clear relationship between the size of residue in the native amino acid and the degree of the impairment in fast inactivation. Figure 7A and B show the current families of A438C and I1589C, respectively. A438W and I1590W exhibited significantly impaired fast inactivation but A438C and I1590C do not (Figures 2,4). In contrast, I1589C displayed impaired fast inactivation similar to that of I1589W (Figure 4). This lack of direct correlation in volume suggests that either allosteric effects occur after amino acid substitutions (i.e. the sulfhydryl undergoes reaction with a nearby bulky, hydrophobic nucleophile) or these residues may specifically and directly interact with other parts of channel structure, such as the inactivation gate.

[0056] Gating properties of double and triple substitutions of residues within D1S6 and D4S6 were also tested. Selected residues (L435, L437, A438, I1589, I1590) were multiply substituted. Several multiple-substituted mutants expressed a high level of Na⁺ currents comparable to that of wild type. There were two distinct types of phenotypes from these mutants. One type showed supra-additive effects on the fast inactivation and the other showed sub-additive effects. Figure 8A, B, C and D show the current families of A438W/I1589W, L437C/A438W, L435W/L437C/A438W, and I1589W/I1590W, respectively. The results thus demonstrate that it is feasible to create fast-inactivation deficient mutants that express well in a mammalian expression system.

[0057] When the fast inactivation was hampered by pronase or by site-directed mutagenesis, slow inactivation gating not only remained functional but also was accelerated considerably. This inverse relationship suggests that the fast inactivation and slow inactivation gating have distinct identities and yet these two gating processes are somehow coupled. To determine whether such inverse relationship holds true in S6 mutants with severely impaired fast inactivation, we therefore measured the slow inactivation gating with a 10-s conditioning prepulse at various voltages. With a gap of 100 ms at -140 mV, which allowed channels to recover from their fast inactivation but not from their slow inactivation, we observed that $57.1 \pm 3.6\%$ ($n = 5$) of wild type Na⁺ currents were slow inactivated at 0 mV for 10 s (Fig. 9A; open circles). In contrast, almost all L435W/L437C/A438W mutant channels were slow-inactivated (Fig. 9A, closed circles) at 0 mV under these experimental conditions. It appeared that this enhanced slow inactivation is in part due to the enhanced forward rate constant as shown in figure 9B. Multiple-substituted mutants with enhanced slow inactivation were inactivated with a rather rapid rate, with a time constant of < 1 sec at +30 mV (vs. 4.8 s for wild type). It is noteworthy that slow inactivation in wild type channels does not reach its steady state with a 10-s conditioning pulse even at +30 mV (Fig. 9B). Nonetheless, this pulse protocol allowed us to determine which mutants exhibit altered slow inactivation significantly. In

general, we observed that mutants with the most impaired fast inactivation (L435, L437, A438, I1589, I1590) were those with enhanced slow inactivation. In particular, the multiple-substituted mutants, such as L437C/A438W and L435W/L437C/A438W, with the most impaired fast inactivation also had the most enhanced slow inactivation.

[0058] The study demonstrates that most mutants with a single W substitution at the C-terminus of D1S6 and D4S6 express observable Na⁺ currents in HEK293t cells. Substitutions with W in this region alter Na⁺ channel activation, fast inactivation, and/or slow inactivation gating in varying degrees, dependent on the position of the substitution. Five positions (L435, L437, A438, I1589, and I1590) appear to be closely associated with fast inactivation gating. Two mutants (L437C/A438W and L435W/L437C/A438W) with multiple W or C substitutions exhibit minimal fast inactivation. Interestingly, all mutants with impaired fast inactivation display an enhanced slow inactivation phenotype. The order of the level of the maintained current in D1S6/D4S6 residues is as follows: A438W (31.9%) > I1590W (20.0%) > I1589C (18.6%) > I1589W (14.5%) > L435W (9.5%) > L437C (6.7%) > L437W (5.5%) > wild type (2.9%). The amount of maintained current of L437W and L437C is higher than that of the wild type but it did not reach the level of statistical significance. In comparison, Nav1.2-L421C (equivalent to Nav1.4-L437C) has a maintained current of ~10% of the peak current, significantly higher than its wild type (~2%). Evidently, differences in the amount of maintained currents exist between mutants derived from different isoforms. The magnitude of the slow inactivation and the fast inactivation appear to have an apparent inverse relationship. The fraction of slow-inactivated channels followed the order I1590W (85.9%) > I1589W (80.6%) > A438W (76.6%) > L435W (75.5%) > L437W (58.7%) > wild type (43.0%) at 0 mV (Fig. 10); these mutants happened to be five residues with impaired fast inactivation. Furthermore, L435W/L437C/A438W, L437C/A438W, and A438W/I1589W mutants with multiple substitutions have

minimal fast inactivation, and they show significantly enhanced slow inactivation (96.8%, 93.2%, and 88.3%, respectively).

[0059] It is surprising to find that the mutants with minimal fast inactivation express as well as the wild type in mammalian cells. Previous reports in the literature indicated that, unlike wild-type Na⁺ channels, various fast-inactivation deficient mutants at the IFM motif expressed poorly in HEK293 expression system under the same conditions. The inactivation-deficient S6 mutants of the invention are useful tools for future studies, including the establishment of permanent cell lines, the screening for potent open-channel blockers that block persistent opening (e.g. anti-arrhythmic agents), the ion permeation in the persistent open channel, and the detailed studies on direct interactions between drugs and the open channel.

[0060] Studies with rNav1.4-L435W/L437C/A438W demonstrated that flecainide binds rapidly and preferentially with the open state but minimally with the resting state. Flecainide is very effective in blocking persistent late Na⁺ currents as evident from its strong time-dependent block of maintained currents during prolonged depolarization. Flecainide binding with the inactivated state is considerably slower than that with the open state by orders of magnitude. Once the channel is blocked by flecainide, the inactivation gate may stabilize receptor-flecainide complex, as the dissociation rate of flecainide is extremely slow and requires $\geq 1,000$ s (~17 minutes) for the full recovery.

[0061] We first measured the Na⁺ current family at voltages ranging from -60 mV to +50 mV. We then applied 30 mM flecainide externally and measured the Na⁺ current at +50 mV for 5ms at a 30-s interval. About 50% of the peak currents were inhibited after flecainide block reached its steady state, usually within 5-7 minutes. We then re-measured the Na⁺ current family in the presence of 30 mM flecainide and found that the current kinetics remained unchanged and the conductance/voltage curves remained comparable with or without flecainide.

[0062] The steady-state inactivation of Na⁺ channels was measured by a standard two-pulse protocol at a test pulse of +30 mV with various conditioning pulses ranging from –160 mV to –15 mV for 100 ms, with and without flecainide. There was a leftward shift of a few mV and the slope factor appeared less steep.

[0063] We applied a voltage scanning protocol ranging from –180 mV to 0 mV to determine whether distinct binding affinities of flecainide exist in rNav1.4 Na⁺ channels. This pulse protocol consisted of a conditioning pulse at various voltages with a 10-s duration intended for drug binding. It was originally designed to test if inactivated channels have higher “saturable” affinities than resting channels for local anesthetics. **Figure 11** shows that flecainide at 30 μM blocks resting channels at a constant level from –180 mV to –100 mV. The block increases continuously from –80 mV to –20 mV.

[0064] We measured the dose-response curve of flecainide with a 10-s conditioning pulse at -140 mV, -70 mV, and -20 mV, again at a 30-s interval for the flecainide to reach steady state. Binding at these three voltages for local anesthetics generally represents the resting, closed/inactivated, and open/inactivated affinities, respectively. The measurements at -20 mV, -70 mV, and -140 mV provided IC₅₀ values of 13.4 ± 0.3 , 21.2 ± 0.4 , and 31.9 ± 3.0 mM, respectively. The difference between the high and low flecainide affinities is less than 3-fold. In the case of cocaine, the difference between the resting and inactivated block is 28-fold (250 mM vs. 9 mM).

[0065] One possibility for the rightward shift of the voltage dependence of flecainide block is that the inactivated channels interact with the drug rather slowly. This appeared to be the case for the development of the inactivated block at –50 mV with a time constant of 10.9 ± 1.3 s. Once developed, the recovery from this inactivated block by flecainide at 100 mM was also very slow with a time constant of >100 s, as if flecainide was trapped within the channel. Unexpectedly, the amplitude of the Na⁺ currents continued to increase during this recovery period and reached a level that is 78% to the control amplitude

without flecainide. A same slow time course also occurred after the block was developed at +30 mV. Thus, both closed/inactivated and open/inactivated block by flecainide recovered nearly to the level about ~80% of the control value with the same slow time course. These results indicated that the resting block at -140 mV by flecainide is much less than the block normally measured at the 30-s interval. The estimated IC_{50} for the resting block of flecainide in wild-type channels is 355 mM at -140 mV.

[0066] To test whether flecainide interacts with the open state of Na⁺ channels we therefore applied repetitive pulses for channel activation. Repetitive pulses at 5 Hz for 60 pulses elicited additional use-dependent block of flecainide by ~50%. The total duration of depolarization was 1.44 s (0.024x60). Therefore, it appears that flecainide binds to the open state of Na⁺ channels with a faster rate than that of the inactivated state since the similar long pulse did not elicit a comparable use-dependent block. This being true, keeping the channel open persistently during depolarization enhances the block of flecainide.

[0067] To determine interactions between flecainide and the open state directly, we used inactivation-deficient rNav1.4-L435W/L437C/A438W mutant channels of the invention. This mutant channel inactivated minimally during depolarization; instead, a substantial fraction of peak current was maintained.

Figure 12 shows the current families before and after flecainide at various concentrations ranging from 0.1 to 30 μ M. At +50 mV, there was a strong time-dependent block of the maintained Na⁺ currents. This result therefore provides the direct evidence that flecainide binds preferentially with the open state of the Na⁺ channel and indicates that Nav mutants of the invention can be used as tools for detailed studies on sodium channel block.

[0068] We generated non-inactivating Na⁺ currents using a test pulse of +30 mV and then measured the time-dependent block of flecainide at various concentrations. The decay phase of the Na⁺ current could be well fitted with a single exponential function and the time constant (τ) was inverted and plotted

against the corresponding concentration (**Figure 13**). The on-rate and off-rate constant of flecainide with the open channel are estimated to be $11.8 \mu\text{M}^{-1}\text{s}^{-1}$ (the slope factor) and 14.8 s^{-1} (y-intercept), respectively. The calculated dissociation constant yields 0.80 mM . The IC_{50} values for the open (estimated block at the end of the pulse) and the resting block (estimated block at the peak current) were $0.61 \pm 0.07 \mu\text{M}$ and $208.3 \pm 16.9 \mu\text{M}$, respectively. In contrast, with a conditioning pulse at -50 mV for 10 s , the IC_{50} was $4.1 \pm 0.1 \mu\text{M}$ (estimated block at the peak current) or about 7-fold less potent than that of the open channel block. This suggests channel opening is required for the high-affinity block of flecainide. With limited channel opening around activation threshold of -50 mV , the flecainide affinity is not as high as that of the open channel block.

[0069] Repetitive pulses at 5 Hz demonstrate that flecainide produces an additional use-dependent block in the peak current amplitude. It appeared that this rapid phase of the use-dependent block was caused directly by the time-dependent block of the non-inactivating current during the pulse. This time-dependent block recovers little during the 200-ms interpulse at -140 mV . There was also a slow inhibition of peak currents during repetitive pulses in inactivation-deficient channels even without flecainide.

[0070] From the foregoing results one may conclude that: (1) Flecainide block of the wild-type Na^+ channel developed after channel activation has a very slow recovery time course, up to $10,000 \text{ s}$ (or ~ 17 minutes) at the holding potential of -140 mV . Any pulse protocol that activates Na^+ channels at a frequency as low as one per 30 s will significantly perturb the degree of flecainide block. (2) The resting and open channel affinities differ by ~ 500 -fold in the inactivation-deficient mutant channels of the invention ($0.61 \mu\text{M}$ vs. $307 \mu\text{M}$, respectively). (3) The recovery from the open channel block by flecainide is relatively fast at -140 mV , with a time constant of 11.2 s in inactivation-deficient mutant channels, or several orders faster than that with intact fast inactivation in wild-type Na^+ channels.

[0071] Flecainide appears to interact with the resting state of Na⁺ channels rather weakly. At 100 mM flecainide blocks only about ~20% of peak Na⁺ currents if the cell is not stimulated repetitively in 1,000 s. The calculated IC₅₀ for flecainide block is therefore about 400 μM. It will be difficult to measure this value directly in a single cell having a wild-type Nav protein at various concentrations, since only one test pulse per 17 minutes can be applied for such dose-response assay. In contrast, the IC₅₀ for flecainide block of inactivation-deficient mutant Na⁺ channels of the invention can be estimated directly from the peak current amplitude, which yields 307 ± 19 μM for the resting block.

[0072] Flecainide appears to be a rather pure open channel blocker with minimal interactions with resting state. Flecainide has been shown to be beneficial for the treatment of a number of genetic diseases with mutations on the Na⁺ channel (e.g., Brugada et al., 1999; Windle et al., 2001). Many of these defective channels exhibit persistent late Na⁺ currents lasting hundreds of milliseconds during prolonged depolarization, such as in the cases of DKPQ (Bennett et al., 1995) or hyperkalemic periodic paralysis (Cannon et al., 1991). Recently, Nagatomo et al (2000) found that flecainide preferentially blocks the late Na⁺ currents in the DKPQ mutant. The results above demonstrate that flecainide indeed blocks the maintained persistent Na⁺ currents effectively and rapidly. The therapeutic plasma concentration of flecainide is 0.4 to 2 μM as an antiarrhythmic agent. At this concentration range, a substantial fraction of the persistent late current should be blocked by flecainide, which exhibits an IC₅₀ of 0.61 μM for the open channel. The persistent late currents are likely more vulnerable to flecainide block as the peak currents are rapidly inactivated and may not be blocked in time. The open-channel selective blockers, such as flecainide and pilsicainide have broader applications for various pathological conditions that manifest an increase in persistent late Na⁺ currents in the heart (Saint et al., 1992), in brain (Crill, 1996) or in muscle (Cannon, 1996) and the search for improved agents to treat these pathological conditions is greatly advanced by the screen of the present invention.